Original Research Article

Research on Process Similarity Matching Method for Aircraft Skin Parts

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Abstracts: **Aim:** Based on aircraft skin processing technology and aircraft skin part similarity matching algorithm, a similarity matching system of aircraft skin part has been developed. **Method:** Key feature parameters of aircraft skin parts forming process are accurately extracted by the cross-sectional method. The nearest neighbor strategy is adopted to quickly search all process design cases in the knowledge lib. The process feature matrix is standardized by interpolation method, effectively dealing with the problem of inconsistent process feature parameter. The stability and reliability of traditional TOPSIS algorithm are improved by a robust standardization algorithm to eliminate the influence of extreme values. **Results:** A system of aircraft skin process feature recognition and matching system was developed based on CAA technology. **Conclusion:** The system has achieved an accuracy rate of 85% on searching for typical aircraft skin parts processes in typical enterprises of aircraft. The developed system can effectively improve the efficiency of aircraft skin part process design.

Keywords: Aircraft Skin; Feature Recognition; Instance Retrieval; Nearest Neighbor Strategy

1. Introduction

Aircraft skin parts are key components of the aircraft's external structure in the fuselage, tail, and wings. With the development of aircraft, the design complexity and size of skin parts keeps increasing. And the demand for precision in dimensions and surface quality has been higher and higher. So, the integrated application of digital process design, manufacturing, and inspection technologies has become a major direction for the advancement of sheet metal process technology, which is critical for ensuring part forming accuracy, achieving rapid assembly.

In traditional aircraft skin part forming process design, there is an over-reliance on the experience judgment of designers. This not only makes the design process complex and tedious but also limits the improvement of design precision. Moreover, designers have to repeat laborious tasks for the large number of similar aircraft parts because of the lack of knowledge reuse in the current design process which extends the production cycle. Therefore, the efficient reuse of design knowledge is widely recognized as a key strategy for improving product design efficiency. The application of case-based reasoning methods has been proven to play a crucial role in enhancing the efficiency of preliminary design.

The core of feature extraction for aircraft skin lies in the comprehensive application of multiple analysis methods to deeply explore the shape or topology of model and to establish a unique and highly distinguishable feature representation for each model. 3D model feature extraction techniques include geometry-based analysis, statistical feature extraction, view-based feature extraction, topology-based feature extraction, and deep learning-based feature extraction. While these techniques perform well in many fields, as the specific shape and forming process of aircraft skin, there is a need to develop a new method that closely combines the feature parameters with the processing technology of the skin.

This article is based on the process of aircraft skin to extract key feature parameters by the cross-sectional method. The system retrieves cases in the database by the nearest neighbor algorithm. On the applying feature matrix standardization and local similarity calculation algorithms, the system achieves precise similarity calculations. Through validation in practical cases, this system has proven to be highly efficient and practical. The developed system greatly promotes the reuse of process and effectively shortens the part manufacturing cycle.

2. Knowledge Base and Knowledge Reuse Process

The knowledge reuse system is specifically designed to meet the actual production needs of aircraft skin stretch-forming design, achieving knowledge-driven mold surface design, simulation optimization design, and automated numerical control programming. The knowledge base, as the foundation of the knowledge-driven system, includes a rule base, template base, and feature parameter base, as shown in **Figure 1**.

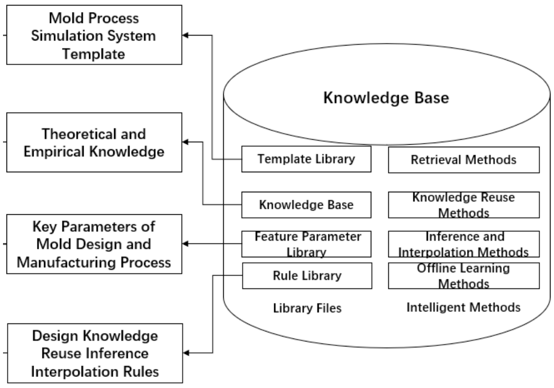

Figure 1. Knowledge Lib Structure.

In the aircraft skin process plan design process, designers first extract key feature parameters based on the input part data. The system calculates the similarity between the current design task and the stored part features in the database to identify the most similar historical case. Once the most similar case is selected, the system uses knowledge-driven methods to automatically adopt similar process parameters through rule-based design for the new part. If the instance meets specific design standards, it is added to the knowledge database, which will enrich the content of the knowledge base. If the instance does not meet the design requirements, the designer needs to make modifications. Once the design requirements are met, the instance will also be added to the database.

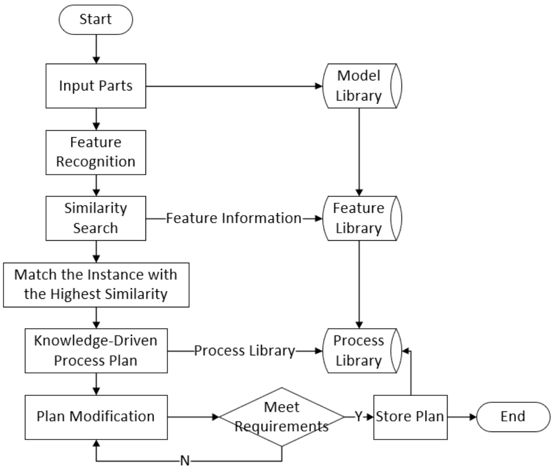

Figure 2. Knowledge-Driven Design Process.

3. Aircraft Skin Feature Parameter Extraction

3.1. Feature Parameter Identification

Aircraft skin is typically a complex 3D surface. In the process design, the feature parameters are related with the selection of processing technologies to ensure consistency in process parameters for parts with similar feature parameters.

In the production process of aircraft skin, stretch forming is one of the most important forming methods. In stretch forming, the curvature and wrap angle of the skin significantly influence the forming quality. Therefore, key feature parameters include the curvature, height, and wrap angle of specific cross-sectional lines on the surface.

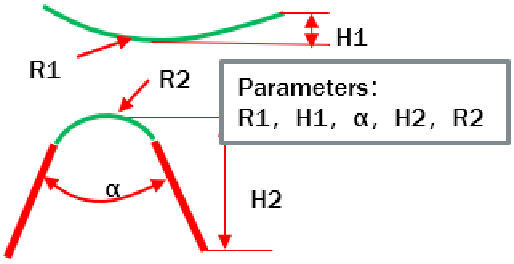

Figure 3. Schematic Diagram of Feature Parameters.

3.2. Feature Parameter Extraction Algorithm

The stretch coordinate system not only determines the spatial positioning of the part but also directly affects the accuracy of feature parameters. The Z-axis of the stretch coordinate system is same with the mold's movement direction, the X-axis follows the lateral movement direction of the clamps, and the Y-axis is perpendicular to both the Z-axis and X-axis.

Based on the stretch coordinate system, this article constructs a rectangular bounding box corresponding to the primary directional coordinate system to capture the maximum and minimum values in the Y-axis direction. The Y-axis is uniformly divided to form equidistant cross-sections parallel to the XOZ plane. The section lines are generated by intersecting the cross-sections with the part. Designers can adjust these sectional lines in the system, especially in areas where curvature changes are more significant, where are important to fully and accurately describe the surface shape. Key feature parameters, including height (H), curvature (R), and wrap angle (A), are extracted on each sectional line, and the relative coordinates of the sectional line to the entire part (RC) are also calculated. The formula is as follows:

$$RC = \frac{Y - Y_{min}}{Y_{max} - Y_{min}}$$

All feature parameters and their relative coordinates on the sectional lines are integrated into a feature parameter matrix, which compactly encodes the geometric attributes of the part. Each row of the matrix represents a sectional line, and each column represents a feature parameter.

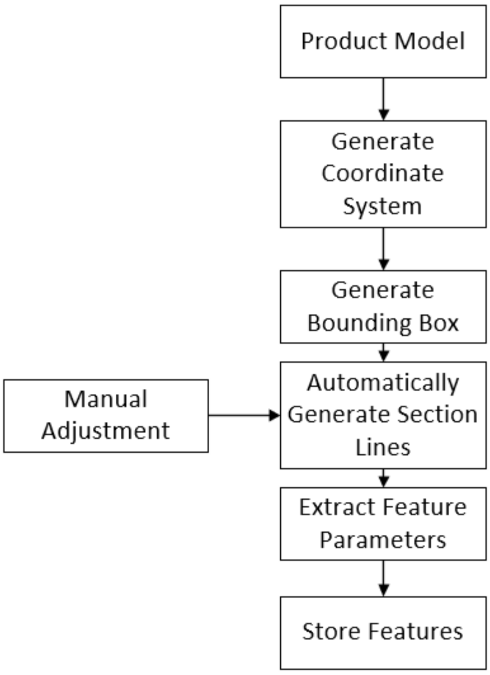

Figure 4. Feature Parameter Extraction Process.

4. Aircraft Skin Instance Retrieval

4.1. Aircraft Skin Instance Retrieval Strategy

Instance retrieval involves using specific algorithms to efficiently identify historical part instances most similar to the current one. An excellent retrieval strategy must satisfy three basic requirements: effectiveness, precision, and speed. This research adopts the nearest neighbor strategy as the core method for retrieval. By calculating the similarity between the target part and all instances in the database, it identifies the instance with the highest similarity. During the instance retrieval process, similarity is the key measure of the resemblance between parts, and feature weights are used to assess the impact of different features on overall similarity. The overall similarity is calculated by combining the local similarity of each feature with the corresponding feature weight, using a weighted sum method, as shown in Formula (1):

$$Sim(X,Y) = \frac{\sum_i Sim_i(X,Y) \times B_i}{\sum_i B_i} \tag{1}$$

Where XY represents the current part and reference part, Sim(XY) represents the overall similarity between the current part and the reference part, and Bi is the feature weight.

4.2. Feature Matrix Standardization Algorithm

In the comparison process of the feature matrix for aircraft skin parts, there are two key issues: first, the number of cross-sectional lines may vary between different parts; second, the positions of the cross-sectional lines may not align. These issues lead to inconsistencies in the feature matrix comparison, resulting in distorted comparison outcomes. To address these issues, this article uses an interpolation method to standardize the feature parameter matrix, aiming to achieve consistency and comparability of feature vectors.

Based on the original feature matrix (M), a series of virtual cross-sectional lines are constructed. These virtual cross-sectional lines have consistent numbers and positions relative to the entire part, evenly distributed along the part's length from 0 to 0.99.

For virtual cross-sectional lines that lack actual sectional lines on the left or right side, interpolation is performed using the real sectional lines on both sides. The standardization process of the feature matrix is achieved by introducing virtual cross-sectional lines and applying interpolation methods. To ensure the accuracy of the interface parameter calculation for virtual cross-sectional lines, different weights are assigned to each virtual cross-sectional line based on its proximity to real cross-sectional lines, enhancing the accuracy of the standardization process.

4.3. Local Similarity Calculation Algorithm

The calculation of local similarity is achieved by comprehensively considering information from both attribute and dimensions. The article uses an improved TOPSIS method to evaluate local similarity. This method ranks objects by comparing their distances to an ideal solution and a negative ideal solution. The traditional TOPSIS method may be affected by outliers, which could lead to a reduction in the differentiation of similarity between parts. The article introduces a robust standardization method to minimize the impact of extreme values.

The matrix standardization method normalizes the feature vector values based on different positional parameters, as shown in Equation (2):

$$\boldsymbol{z_{ij}} = \frac{\boldsymbol{2y_{\frac{1}{2}} - y_{ij}}}{\boldsymbol{y_{\frac{3}{4}} - y_{\frac{1}{4}}}} \tag{2}$$

Where $\boldsymbol{y_{\frac{1}{2}}}$ represents the median, $\boldsymbol{y_{\frac{3}{4}}}$ represents the third quartile, and $\boldsymbol{y_{\frac{1}{4}}}$ represents the first quartile. Through this standardization method, the local similarity between parts is quantitatively evaluated, providing scientific support for knowledge reuse and process design.

5. Application Example

The knowledge reuse system developed in this study was applied to the manufacturing process of aircraft skin in a company, where several real parts were analyzed as case studies.

In the system's database, multiple historical part cases have already been stored, each with detailed process information and design parameters. In this example, we selected six parts labeled c1 to c6 as references. The original parts are shown in **Figure 5**.

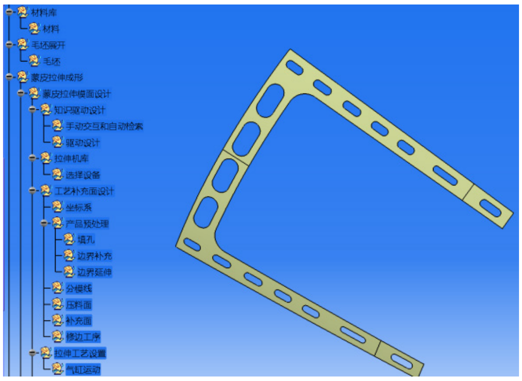

Figure 5. Original Part.

Table 1. Similarity Calculation Results.

Part	**c1**	**c2**	**c3**	**c4**	**c5**	**c6**
Similarity	0.68	0.79	0.57	0.81	0.63	0.51

The system normalized the feature data of the target part and calculated the local similarity between the target part and each reference part in the database. The overall similarity score was obtained by combining these local similarity results. As shown in **Table 1**, part c4 has the highest similarity to the target part, with a score of 0.81, indicating that its process plan is the closest to the target part.

Based on the process plan of part c4, the knowledge reuse system was used to design the simulation mold surface for the target part, as shown in **Figure 7**. The design results of the simulated mold surface not only meet the requirements of process design but also significantly shorten the design cycle compared to manual design.

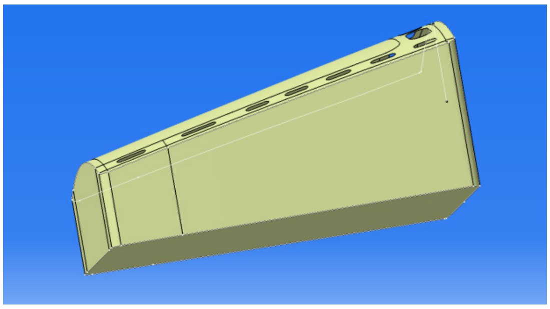

Figure 6. Knowledge Reuse Results.

6. Conclusion

This research addresses the challenges of knowledge reuse in the process design of aircraft skin parts by developing an innovative knowledge reuse system that significantly enhances the efficiency and quality of process design reuse.

The core advantage of this system lies in its ability to automatically identify feature parameters that are closely related to the manufacturing process. Using the cross-sectional method, the system extracts key shape features from aircraft skin parts. Through the nearest neighbor strategy, it efficiently retrieves the most similar instances from the database for the target part. During the similarity matrix calculation process, the feature matrix standardization algorithm and the improved TOPSIS algorithm improve the accuracy and robustness of the similarity calculation.

Validated through practical case studies, this system demonstrates excellent performance in aircraft skin part design tasks driven by knowledge reuse, significantly reducing the design process time and error rate.

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